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Value Functions and Transversality Conditions for Infinite-Horizon Optimal Control Problems*

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Abstract

This paper investigates a relationship between the maximum principle with an infinite horizon and dynamic programming and sheds new light upon the role of the transversality condition at infinity as necessary and sufficient conditions for optimality with or without convexity assumptions. We first derive the nonsmooth maximum principle and the adjoint inclusion for the value function as necessary conditions for optimality that exhibit a relationship between the maximum principle and dynamic programming. We then present sufficiency theorems that are consistent with the strengthened maximum principle, employing the adjoint inequalities for the Hamiltonian and the value function. Synthesizing these results, necessary and sufficient conditions for optimality are provided for the convex case. In particular, the role of the transversality conditions at infinity is clarified.

Key Words: Nonsmooth maximum principle; Infinite horizon; Value function; Transversality condition; Adjoint inclusion; Necessary and sufficient conditions.

MSC2000: 49K24, 49L20.

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1 Introduction

The maximum principle in optimal control is a fundamental instrument in dynamic optimization theory. It is usually formulated in a finite horizon, but one often needs to treat the case for an infinite horizon, especially in economic growth theory. While the maximum principle with an infinite horizon was treated in a simple manner by Pontryagin et al. [29, Section 24], it was Shell [34] (later Halkin [24]) who first pointed out, by way of counterexample, that the transversality condition with a finite horizon cannot be extended in an intuitive way to that with an infinite horizon as a part of necessary conditions for optimality. Since then, the maximum principle with an infinite horizon has been elaborated by, for instance, Aseev and Kryaziimskiy [3], Aubin and Clarke [4], Cartigny and Michel [14], Feinstein and Luenberger [21], Michel [27], Seierstadt and Sydsæter [33] and Ye [39] with primal attention to the transversality condition at infinity.

On the other hand, solutions to optimal control problems can be characterized by dynamic programming, which is based on the value function as a solution to the Hamilton–Jacobi–Bellman (HJB) equation. Under some regularity conditions, the value function is a smooth solution to the HJB equation. It is well-known, however, that the regularity conditions are violated in many cases of interest and the value function fails to be continuously differentiable even if the underlying data are smooth. Indeed, one may expect the value function to be, at best, Lipschitz continuous, even in the smooth data case. (For the differentiability of the value function, see Cannarsa and Frankowska [13].)

To overcome this difficulty, there exist two lines of research. One is “nonsmooth analysis” initiated by Clarke [16, 17], which employs generalized gradients of the value function and generalized solutions to the extended HJB equation, and the linkage between the maximum principle and dynamic programming has been established by Clarke and Vinter [18] and Vinter [37]. The other, a somewhat later development, is the concept of “viscosity solutions” to the HJB equation, which makes use of the notion of super- and subdifferentials, proposed by Crandall and Lions [19] and Crandall, Evans and Lions [20]. The value function is shown to be a unique viscosity solution of the HJB equation and the connection between the adjoint equation for the Hamiltonian and that for the value function has been investigated by Barron and Jensen [7], Cannarsa and Frankowska [13], Frankowska [22], Mirică [28] and Zhou [42]. For relations between viscosity solutions to the HJB equation and generalized solutions to the extended HJB equation, see Frankowska [23] and Zhou [43].

The purpose of this paper is to investigate a relationship between the maximum principle with an infinite horizon and dynamic programming and shed new light upon the role of the transversality condition at infinity as necessary and sufficient conditions for optimality with or without convexity assumptions.

In this paper, we mitigate the smoothness assumptions by introducing the technique of nonsmooth analysis along the lines of Clarke [16, 17]. We first derive the nonsmooth maximum principle and the adjoint inclusion for the value function as necessary conditions for optimality that exhibit a relationship between the maximum principle and dynamic programming. The necessary conditions under consideration are direct extensions of those of Clarke and Vinter [18] and Vinter [37] to an infinite horizon setting. The nonsmooth maximum principle with an infinite horizon demonstrated by Ye [39] is generalized by taking into

account unbounded controls and nonautonomous systems.

We then present sufficient conditions for optimality under nonsmooth non-convex hypotheses. Two sufficiency theorems are provided. The first is an extension of the finite horizon result by Zeidan [40, 41] to the infinite horizon setting, which is stated in terms of the adjoint inequality for the Hamiltonian that is consistent with the strengthened maximum principle. The second, which exploits the adjoint inequality for the value function, is novel in the literature in that the sufficient condition is related to the adjoint inclusion of the value function as well as the adjoint inequality for the Hamiltonian.

Synthesizing these results, it is possible to characterize optimal solutions and provide necessary and sufficient conditions for optimality if one restricts attention to the convex case. In particular, the role of the transversality conditions at infinity is clarified. This characterization is analogous to the result for the finite horizon case by Rockafeller [30], who systematically developed dual problems of optimal control under convexity hypotheses. To this end, the convexity of the value function and the concavity of the Hamiltonian are established.

2 Preliminary

This section collects some preliminary results on generalized gradients for locally Lipschitz functions. When the function under investigation is a convex function, the results are reduced to the traditional subdifferential calculus. A basic reference for the results treated in this section is Clarke [16].

Denote by $\langle x, y \rangle$ the inner product of the points $x, y \in \mathbb{R}^n$. The norm of x is given by $\|x\| = \langle x, x \rangle^{\frac{1}{2}}$. A function $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is *Lipschitz of rank* $K \geq 0$ near a given point $x \in \mathbb{R}^n$ if there exists some $\varepsilon > 0$ such that:

$$|f(y) - f(z)| \leq K\|y - z\| \quad \text{for every } y, z \in x + \varepsilon B.$$

Here, B is the open unit ball in \mathbb{R}^n . A function f is said to be *locally Lipschitz* on $X \subset \mathbb{R}^n$ if f is Lipschitz near x for every $x \in X$.

Let f be Lipschitz near $x \in \mathbb{R}^n$. The *generalized directional derivative* of f at x in the direction $v \in \mathbb{R}^n$, denoted by $f^\circ(x; v)$, is defined as follows:

$$f^\circ(x; v) = \limsup_{\substack{y \rightarrow x \\ \lambda \downarrow 0}} \frac{f(y + \lambda v) - f(y)}{\lambda}.$$

The *generalized gradient* of f at x , denoted by $\partial f(x)$, is defined by:

$$\partial f(x) = \{\zeta \in \mathbb{R}^n \mid \langle \zeta, v \rangle \leq f^\circ(x; v) \quad \forall v \in \mathbb{R}^n\}.$$

Note that $\partial f(\cdot)$ induces a set-valued mapping from \mathbb{R}^n into itself and we denote it by $\partial f : \mathbb{R}^n \rightrightarrows \mathbb{R}^n$.

The set of points at which a given function f fails to be differentiable is denoted by Ω_f . Rademacher's theorem states that a Lipschitz function on an open subset of \mathbb{R}^n is differentiable almost everywhere on that subset. Thus, if f is Lipschitz near x , then its generalized gradient is given by:

$$\partial f(x) = \text{co} \left\{ \lim_{\nu \rightarrow \infty} \nabla f(x^\nu) \mid x^\nu \rightarrow x, x^\nu \notin N \cup \Omega_f, \nu = 1, 2, \dots \right\},$$

where $\nabla f(x^\nu)$ is the gradient of f at x^ν , N is any set of Lebesgue measure 0 in \mathbb{R}^n and the convex hull is taken over all limit points $\nabla f(x^\nu)$ for which $\{x^\nu\}$ is any sequence converging to x while avoiding the set $N \cup \Omega_f$ and such that $\nabla f(x^\nu)$ converges.

Let $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a vector-valued function, written in terms of component functions as $F(x) = (f_1(x), \dots, f_m(x))$ such that each f_i (and hence F) is Lipschitz near a given point $x \in \mathbb{R}^n$. Denote by $JF(y)$ the $m \times n$ -Jacobian matrix of partial derivatives whenever $y \in \mathbb{R}^n$ is a point at which the partial derivatives exist and by Ω_F the complement of the set of all such points. The *generalized Jacobian* of F at x , denoted by $\partial F(x)$, is defined by:

$$\partial F(x) = \text{co} \left\{ \lim_{\nu \rightarrow \infty} JF(x^\nu) \mid x^\nu \rightarrow x, x^\nu \notin \Omega_F, \nu = 1, 2, \dots \right\}.$$

The meaning of the convex hull is similar as above. It follows that:

$$\partial F(x) \subset \partial f_1(x) \times \dots \times \partial f_m(x),$$

where the right-hand side of the inclusion denotes the set of all matrices whose i th row belongs to $\partial f_i(x)$ for each i .

The half-open interval $[0, \infty)$ of the real line is equipped with the σ -algebra \mathcal{L} of Lebesgue measurable subsets of $[0, \infty)$. Denote the product of the σ -algebra of \mathcal{L} and the σ -algebra $\mathcal{B}^n \times \mathcal{B}^m$ of Borel subsets of the product space $\mathbb{R}^n \times \mathbb{R}^m$ by $\mathcal{L} \times \mathcal{B}^n \times \mathcal{B}^m$.

The t -section of a subset Ω of $[0, \infty) \times \mathbb{R}^n$ is denoted by $\Omega(t)$, that is, $\Omega(t) = \{x \in \mathbb{R}^n \mid (t, x) \in \Omega\}$ for $t \in [0, \infty)$.

For later use, we present the following result.

Theorem 2.1. (i) *Let Ω be an $\mathcal{L} \times \mathcal{B}^n$ -measurable subset of $[0, \infty) \times \mathbb{R}^n$. If $f : \Omega \rightarrow \mathbb{R}$ is an $\mathcal{L} \times \mathcal{B}^n$ -measurable function such that $f(t, \cdot)$ is locally Lipschitz on $\Omega(t)$ for every $t \in [0, \infty)$, then $\partial_x f : \Omega \rightrightarrows \mathbb{R}^n$ is $\mathcal{L} \times \mathcal{B}^n$ -measurable.*

(ii) *Let $x_0 \in \mathbb{R}^n$ and $\varepsilon > 0$ be given. If $f : (x_0 + \varepsilon B) \times \mathbb{R}^m \rightarrow \mathbb{R}$ is upper semicontinuous and $f(\cdot, y)$ is Lipschitz on $x_0 + \varepsilon B$ for every $y \in \mathbb{R}^m$, then $\partial_x f : (x_0 + \varepsilon B) \times \mathbb{R}^m \rightrightarrows \mathbb{R}^n$ is upper semicontinuous.*

3 Necessary Condition for Optimality

We are given $\mathcal{L} \times \mathcal{B}^n \times \mathcal{B}^m$ -measurable functions $L : [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$ and $f : [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n$, an $\mathcal{L} \times \mathcal{B}^n$ -measurable subset Ω of $[0, \infty) \times \mathbb{R}^n$ and a set-valued mapping $U : [0, \infty) \rightrightarrows \mathbb{R}^m$ with the $\mathcal{L} \times \mathcal{B}^m$ -measurable graph. An ε -tube about the continuous function $x : [0, \infty) \rightarrow \mathbb{R}^n$ is a set of the form:

$$T(x(\cdot); \varepsilon) = \{(t, x) \in [0, \infty) \times \mathbb{R}^n \mid x \in x(t) + \varepsilon B\},$$

with $\varepsilon > 0$.

The optimal control problem under investigation is the following:

$$\begin{aligned}
\min J(x(\cdot), u(\cdot)) &:= \int_0^\infty L(t, x(t), u(t)) dt \\
\text{s.t. } \dot{x}(t) &= f(t, x(t), u(t)) \quad \text{a.e. } t \in [0, \infty), \\
x(0) &= x_0, \\
x(t) &\in \Omega(t) \quad \text{for every } t \in [0, \infty), \\
u(t) &\in U(t) \quad \text{a.e. } t \in [0, \infty).
\end{aligned} \tag{P}$$

Here, the minimization is taken over all locally absolutely continuous functions (arcs) $x : [0, \infty) \rightarrow \mathbb{R}^n$ and \mathcal{L} -measurable functions $u : [0, \infty) \rightarrow \mathbb{R}^m$ satisfying the control system for the problem (P).

Because the objective integral functional with an infinite horizon admits its values to be infinite, there are several criteria for optimality (see, for example, Feinstein and Luenberger [21], Halkin [24], Kamihigashi [25], Seierstadt and Sydsæter [33], Takekuma [35]). For simplicity, we restrict ourselves to the class of pairs $(x(\cdot), u(\cdot))$ of functions for which the improper integral converges, as in Aseev and Kryazimskiy [3], Aubin and Clarke [4], Cartigny and Michel [14], Michel [27], Pontryagin et al. [29] and Ye [39].

A *process* on a given subinterval I of $[0, \infty)$ is a pair $(x(\cdot), u(\cdot))$ of functions on I of which $x : I \rightarrow \mathbb{R}^n$ is a locally absolutely continuous function and $u : I \rightarrow \mathbb{R}^m$ is a measurable function such that the control system for (P) with I in place of $[0, \infty)$ and the initial condition $x(t) = x_0$, where t is the left endpoint of I , is satisfied. A process $(x(\cdot), u(\cdot))$ on I is *admissible* if the integrand $L(\cdot, x(\cdot), u(\cdot))$ is integrable on I . A process on I is *minimizing* if it minimizes the value of the integral functional $\int_I L dt$ over all admissible processes on I . When $I = [0, \infty)$, we shall abbreviate the domain on which processes are defined. In this section, $(x_0(\cdot), u_0(\cdot))$ is taken to be a fixed minimizing process on $[0, \infty)$ for (P).

We define the value function $V : \Omega \rightarrow \mathbb{R} \cup \{\pm\infty\}$ by:

$$V(t, x) = \inf \left\{ \int_t^\infty L(s, x(s), u(s)) ds \right\},$$

where the infimum is taken over all admissible processes $(x(\cdot), u(\cdot))$ on $[t, \infty)$ for which $x(t) = x \in \Omega(t)$. When no such admissible processes exist, the value is supposed to be $+\infty$, as usual.

3.1 Maximum Principle with an Infinite Horizon

The basic hypotheses to derive necessary conditions for optimality are as follows.

- Hypothesis 3.1.** (i) $L(\cdot, x, \cdot)$ is measurable for every $x \in \mathbb{R}^n$ and $L(t, \cdot, u)$ is Lipschitz of rank $k_L(t)$ on $\Omega(t)$ for every $(t, u) \in \text{graph}(U)$ with k_L an integrable function.
- (ii) There exists an integrable function φ on $[0, \infty)$ such that $|L(t, x_0(t), u)| \leq \varphi(t)$ for every $(t, u) \in \text{graph}(U)$.
- (iii) $f(\cdot, x, \cdot)$ is measurable for every $x \in \mathbb{R}^n$ and $f(t, \cdot, u)$ is Lipschitz of rank $k_f(t)$ on $\Omega(t)$ for every $(t, u) \in \text{graph}(U)$ with k_f a locally integrable function.

- (iv) The function k on $[0, \infty)$ given by $k(t) := k_L(t) \exp(\int_0^t k_f(s) ds)$ is integrable.
- (v) There exists an ε -tube about $x_0(\cdot)$ contained in Ω such that $V(t, \cdot)$ is Lipschitz of rank K on $x_0(t) + \varepsilon B$ for every $t \in [0, \infty)$.

The Lipschitz continuity of the value function in the condition (v) of the hypothesis is nonstringent because, as seen in Appendix A, the condition is implied from the hypothesis guaranteeing the existence of minimizing processes for every initial condition. In particular, when $\Omega = [0, \infty) \times \mathbb{R}^n$, it is redundant because it is obtained from other conditions (i) to (iv) of the hypothesis.

The Pontryagin (or pseudo) Hamiltonian H_P and the (true) Hamiltonian H for (P) are given respectively by:

$$H_P(t, x, u, p) = \langle p, f(t, x, u) \rangle - L(t, x, u),$$

and

$$H(t, x, p) = \sup_{u \in U(t)} \{ \langle p, f(t, x, u) \rangle - L(t, x, u) \}.$$

Theorem 3.1. *Suppose that Hypothesis 3.1 is satisfied. Then, there exists a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ with the following properties.*

- (i) $-\dot{p}(t) \in \partial_x H_P(t, x_0(t), u_0(t), p(t))$ a.e. $t \in [0, \infty)$.
- (ii) $H_P(t, x_0(t), u_0(t), p(t)) = H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$.
- (iii) $-p(t) \in \partial_x V(t, x_0(t))$ a.e. $t \in [0, \infty)$.
- (iv) $-p(0) \in \partial_x V(0, x_0(0))$.

Theorem 3.1 does not exclude the possibility that $-p(t) \notin \partial_x V(t, x_0(t))$ for every t in the null set of $[0, \infty)$. The question naturally arises whether this null set can be eliminated in special circumstances. The proof of the following result is the same as that of Clarke and Vinter [18].

Corollary 3.1. *The condition (iii) of Theorem 3.1 can be strengthened to:*

$$-p(t) \in \partial_x V(t, x_0(t)) \quad \text{for every } t \in [0, \infty),$$

if (i) $\partial_x V(\cdot, x_0(\cdot)) : [0, \infty) \rightrightarrows \mathbb{R}^n$ is upper semicontinuous; or (ii) $\Omega(t)$ is convex for every $t \in [0, \infty)$ and $V(t, \cdot)$ is a convex function on $\Omega(t)$ for every $t \in [0, \infty)$.

3.2 Auxiliary Result

Theorem 3.1 can be proven by extending the necessary condition for the finite horizon case provided by Clarke and Vinter [18] to the infinite horizon case. To this end, we introduce a perturbed infinite-horizon optimal control problem with free left endpoints and deduce the maximum principle for it. The adjoint variable of the finite horizon problem restricted to the arbitrarily fixed finite interval $[0, T]$ is extended to $[0, \infty)$ as $T \rightarrow \infty$ by making use of the diagonalization method based on the equicontinuity of the relevant sequence of adjoint variables.

3.2.1 Perturbed Problem

Fix $\varepsilon > 0$ such that the ε -tube about $x_0(\cdot)$ is contained in Ω given in Hypothesis 3.1(v). A triplet $(x(\cdot), u(\cdot), v(\cdot))$ of functions on $[0, \infty)$ is called a *perturbed process* if it satisfies the perturbed control system:

$$\begin{aligned} \dot{x}(t) &= f(t, x(t), u(t)) + v(t) \quad \text{a.e. } t \in [0, \infty), \\ x(t) &\in x_0(t) + \varepsilon B \quad \text{for every } t \in [0, \infty), \\ u(t) &\in U(t) \quad \text{a.e. } t \in [0, \infty), \\ v(t) &\in B \quad \text{a.e. } t \in [0, \infty). \end{aligned}$$

Here, an \mathcal{L} -measurable function $v : [0, \infty) \rightarrow \mathbb{R}^n$ is viewed as a new control function.

Define the function $\sigma_\varepsilon : [0, \infty) \times \mathbb{R}^n \rightarrow \mathbb{R}$ by:

$$\sigma_\varepsilon(t, v) = \max\{\langle p, v \rangle \mid p \in \partial_x V(t, x_0(t) + \varepsilon \bar{B})\}.$$

Here, \bar{B} is the closure of B . Since $\partial_x V(t, \cdot)$ is compact-valued and upper semi-continuous (see Clarke [16, Proposition 2.1.1]), $\partial_x V(t, x_0(t) + \varepsilon \bar{B})$ is compact for every $t \in [0, \infty)$. Therefore, the maximum in the above is indeed attained.

Lemma 3.1. (i) σ_ε is $\mathcal{L} \times \mathcal{B}^n$ -measurable and $\sigma_\varepsilon(t, \cdot)$ is continuous for every $t \in [0, \infty)$;

(ii) $\sigma_\varepsilon(\cdot, v(\cdot))$ is locally integrable on $[0, \infty)$ if $v(\cdot)$ is locally integrable on $[0, \infty)$.

The following result is an obvious extension of Clarke and Vinter [18, Lemma 8.4].

Lemma 3.2. If $(x(\cdot), u(\cdot), v(\cdot))$ is a perturbed process, then:

$$\int_0^t L(s, x(s), u(s)) ds + \int_0^t \sigma_\varepsilon(s, -v(s)) ds - V(0, x(0)) \geq 0,$$

for every $t \in [0, \infty)$ with the equality at $(x_0(\cdot), u_0(\cdot), v(\cdot) \equiv 0)$.

Consider the following perturbed infinite-horizon optimal control problem with free left endpoints:

$$\begin{aligned} \min & \int_0^\infty L(t, x(t), u(t)) dt + \int_0^\infty \sigma_\varepsilon(t, -v(t)) dt - V(0, x(0)) \\ \text{s.t. } & \dot{x}(t) = f(t, x(t), u(t)) + v(t) \quad \text{a.e. } t \in [0, \infty), \\ & x(t) \in x_0(t) + \varepsilon B \quad \text{for every } t \in [0, \infty), \\ & u(t) \in U(t) \quad \text{a.e. } t \in [0, \infty), \\ & v(t) \in B \quad \text{a.e. } t \in [0, \infty). \end{aligned} \tag{P_\varepsilon}$$

Here, $u(\cdot)$ and $v(\cdot)$ are control functions and $x(\cdot)$ is a state function. Note that, by Hypothesis 3.1, for every perturbed process $(x(\cdot), u(\cdot), v(\cdot))$, we have:

$$\begin{aligned} & |L(t, x(t), u(t)) - L(t, x_0(t), u_0(t))| \\ & \leq |L(t, x(t), u(t)) - L(t, x_0(t), u(t))| + |L(t, x_0(t), u(t)) - L(t, x_0(t), u_0(t))| \end{aligned}$$

$$\begin{aligned} &\leq k_L(t)\|x(t) - x_0(t)\| + 2\varphi(t) \\ &\leq \varepsilon k_L(t) + 2\varphi(t), \end{aligned}$$

a.e. $t \in [0, \infty)$. Thus, the improper integral $\int_0^\infty L dt$ converges over all perturbed process. A perturbed process is *admissible* for the problem (P_ε) if the improper integral $\int_0^\infty \sigma_\varepsilon dt$ converges. A minimizing process for (P_ε) is a perturbed process that minimizes the objective integral functional of (P_ε) over all admissible process. By Lemma 3.2, $(x_0(\cdot), u_0(\cdot), v(\cdot) \equiv 0)$ is a minimizing process for (P_ε) .

3.2.2 Necessary Condition for the Perturbed Problem

Let $l : \mathbb{R}^n \rightarrow \mathbb{R}$ be locally Lipschitz. Consider the following free left and right endpoint infinite-horizon problem:

$$\begin{aligned} \min \quad & l(x(0)) + \int_0^\infty L(t, x(t), u(t)) dt \\ \text{s.t.} \quad & \dot{x}(t) = f(t, x(t), u(t)) \quad \text{a.e. } t \in [0, \infty), \\ & x(t) \in \Omega(t) \quad \text{for every } t \in [0, \infty), \\ & u(t) \in U(t) \quad \text{a.e. } t \in [0, \infty). \end{aligned} \tag{Q^\infty}$$

We say that a process is admissible for the problem (Q^∞) if the improper integral $\int_0^\infty L dt$ converges.

A necessary condition for (P_ε) is obtained from that for the more general problem (Q^∞) . While the following result was exploited by Ye [39] with a sketchy outline of the proof, the suggested proof requires an adequate diagonalization method. For completeness, we render an alternative proof. (The compactness argument in Step 3 in the sequel is where we depart from the argument by Ye [39].)

Theorem 3.2. *Let $(x_0(\cdot), u_0(\cdot))$ be a minimizing process for (Q^∞) with Hypothesis 3.1. Then, there exists a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ such that*

- (i) $-\dot{p}(t) \in \partial_x H_P(t, x_0(t), u_0(t), p(t))$ a.e. $t \in [0, \infty)$,
- (ii) $H_P(t, x_0(t), u_0(t), p(t)) = H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$,
- (iii) $p(0) \in \partial l(x_0(0))$.

3.3 Proof of Theorem 3.1

Now, back to the necessary condition for (P_ε) . Since $(x_0(\cdot), u_0(\cdot), v(\cdot) \equiv 0)$ is a minimizing process for (P_ε) by Lemma 3.2, it follows from Theorem 3.2 that there exists a locally absolutely continuous function $p_\varepsilon : [0, \infty) \rightarrow \mathbb{R}^n$ such that

- (1) $-\dot{p}_\varepsilon(t) \in \partial_x H_P(t, x_0(t), u_0(t), p_\varepsilon(t))$ a.e. $t \in [0, \infty)$,
- (2) $H_P(t, x_0(t), u_0(t), p_\varepsilon(t)) = H(t, x_0(t), p_\varepsilon(t))$ a.e. $t \in [0, \infty)$,
- (3) $\max_{v \in B} \{\langle p_\varepsilon(t), v \rangle - \sigma_\varepsilon(t, -v)\} = 0$ a.e. $t \in [0, \infty)$,
- (4) $-p_\varepsilon(0) \in \partial_x V(0, x_0(0))$.

Since $\|\dot{p}_\varepsilon(t)\| \leq \psi(t)$ a.e. $t \in [0, \infty)$ and $\|p_\varepsilon(t)\| \leq K + \int_0^t \psi(s)ds$ for every $t \in [0, \infty)$ with $\psi(t) = Kk_f(t) \exp(\int_0^t k_f(s)ds) + k_L(t)$, where K is the Lipschitz bound of $V(0, \cdot)$ given in Hypothesis 3.1(v). Thus, the net $\{p_\varepsilon(\cdot)\}$ is an equicontinuous family of locally absolutely continuous functions on $[0, \infty)$ and, hence, the similar diagonalization process as in Step 3 of the proof of Theorem 3.2 yields: there exists a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ such that, for every compact subset I of $[0, \infty)$, the net $\{p_\varepsilon(\cdot)\}$ contains a subnet (which we do not relabel) such that $p_\varepsilon(\cdot)$ converges uniformly to $p(\cdot)$ on I and $\dot{p}_\varepsilon(\cdot)$ converges weakly to $\dot{p}(\cdot)$ in $L^1(I; \mathbb{R}^n)$ as $\varepsilon \rightarrow 0$. Therefore, by taking the limits in the conditions (1), (2) and (4) along a suitable subnet as in Step 4 of the proof of Theorem 3.2, at the limit, we obtain the conditions (i), (ii) and (iv) of the theorem.

Finally, we investigate the implication of the condition (3) according to the argument by Clarke and Vinter [18]. Take a point $t \in [0, \infty)$ at which (3) is true. Then:

$$-p_\varepsilon(t) \in \overline{\text{co}} \partial_x V(t, x_0(t) + \varepsilon \bar{B}) =: \Pi_\varepsilon(t),$$

for otherwise $-p_\varepsilon(t)$ and the closed convex set $\Pi_\varepsilon(t)$ can be strictly separated, i.e., there exists a vector v in B such that:

$$\langle p_\varepsilon(t), v \rangle > \max\{\langle p, v \rangle \mid p \in \Pi_\varepsilon(t)\} = \sigma_\varepsilon(t, -v)$$

in contradiction of (3). Thus, $-p_\varepsilon(t) \in \Pi_\varepsilon(t)$ a.e. $t \in [0, \infty)$ and passing to the limit along a subnet yields:

$$-p(t) \in \bigcap_{\varepsilon > 0} \overline{\text{co}} \partial_x V(t, x_0(t) + \varepsilon \bar{B}) \quad \text{a.e. } t \in [0, \infty). \quad (3.1)$$

We claim that the condition (iii) of the theorem:

$$-p(t) \in \partial_x V(t, x_0(t)) \quad \text{a.e. } t \in [0, \infty),$$

holds. Otherwise, we can strictly separate the point $-p(t)$ and the closed convex set $\partial_x V(t, x_0(t))$, i.e., there exists $v \in \mathbb{R}^n$ and $\delta > 0$ such that:

$$-\langle p(t), v \rangle - \delta > \max\{\langle p, v \rangle \mid p \in \partial_x V(t, x_0(t))\} = V^\circ(t, x_0(t); v).$$

Since the generalized partial derivative $V^\circ(t, \cdot; \cdot)$ is upper semicontinuous (see Clarke [16, Proposition 2.1.1]):

$$-\langle p(t), v \rangle - \frac{1}{2}\delta > V^\circ(t, x; v),$$

whenever $x \in x_0(t) + \varepsilon B \subset \Omega$ for some $\varepsilon > 0$. Then:

$$\begin{aligned} -\langle p(t), v \rangle - \frac{1}{2}\delta &> \sup\{\langle p, v \rangle \mid p \in \partial_x V(t, x_0(t) + \varepsilon \bar{B})\} \\ &= \max\{\langle p, v \rangle \mid p \in \overline{\text{co}} \partial_x V(t, x_0(t) + \varepsilon \bar{B})\}. \end{aligned}$$

But this implies that:

$$-p(t) \notin \overline{\text{co}} \partial_x V(t, x_0(t) + \varepsilon \bar{B}),$$

in contradiction of (3.1). Therefore, the condition (iii) of the theorem is true.

This completes the proof of Theorem 3.1. \square

4 Sufficient Conditions for Optimality

We now turn for the important issue of *sufficient conditions*; that is, conditions that assure that a given admissible process is in fact an optimal solution of the problem.

4.1 Sufficiency Theorems

Definition 4.1. An admissible process $(x_0(\cdot), u_0(\cdot))$ for (P) is *locally minimizing* in $T(x_0(\cdot); \varepsilon)$ if there exists some $\varepsilon > 0$ such that $(x_0(\cdot), u_0(\cdot))$ minimizes the functional $J(x(\cdot), u(\cdot))$ over all admissible processes $(x(\cdot), u(\cdot))$ satisfying $x(t) \in x_0(t) + \varepsilon B$ for every $t \in [0, \infty)$.

Note that, if $\varepsilon = +\infty$, then $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P).

Hypothesis 4.1. (i) $L(t, \cdot, \cdot)$ is lower semicontinuous on $\Omega(t) \times U(t)$ for every $t \in [0, \infty)$.

(ii) $f(t, \cdot, \cdot)$ is continuous on $\Omega(t) \times U(t)$ for every $t \in [0, \infty)$.

(iii) $U(t)$ is closed for every $t \in [0, \infty)$ and $\text{graph}(U)$ is $\mathcal{L} \times \mathcal{B}^m$ -measurable.

(iv) For every $t \in [0, \infty)$ and for every bounded subset Z of $\mathbb{R}^n \times \mathbb{R}^n$, the set:

$$\{u \in U(t) \mid \exists (x, v) \in Z : f(t, x, u) = v\},$$

is bounded.

The following result is an extension of Zeidan [41] to the infinite horizon case.

Theorem 4.1. Suppose that Hypothesis 4.1 is satisfied. Let $(x_0(\cdot), u_0(\cdot))$ be an admissible process for (P) such that there exist a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$, a locally absolutely continuous $n \times n$ -symmetric matrix-valued function P on $[0, \infty)$ and some $\varepsilon > 0$ with the following properties.

(i) For a.e. $t \in [0, \infty)$ and for every $v \in \varepsilon B$ and $u \in U(t)$:

$$\begin{aligned} & H_P(t, x_0(t) + v, u, p(t) - P(t)v) \\ & \leq H_P(t, x_0(t), u_0(t), p(t)) - \langle \dot{p}(t) + P(t)\dot{x}_0(t), v \rangle + \frac{1}{2} \langle v, \dot{P}(t)v \rangle. \end{aligned}$$

(ii) For every $\eta > 0$, there exists some $t_0 \in [0, \infty)$ such that:

$$\frac{1}{2} \langle v, P(t)v \rangle < \langle p(t), v \rangle + \eta \quad \text{for every } v \in \varepsilon B \text{ and } t \in [t_0, \infty).$$

Then, $(x_0(\cdot), u_0(\cdot))$ is a locally minimizing process in $T(x_0(\cdot); \varepsilon)$ for (P).

Note that the condition (i) of the theorem implies the condition (ii) of Theorem 3.1. When $\varepsilon = +\infty$ and the matrix-valued function P in the theorem happens to be identically the zero matrix, the condition (i) of the theorem reduces to the supergradient inequality for H :

$$H(t, x_0(t) + v, p(t)) - H(t, x_0(t), p(t)) \leq -\langle \dot{p}(t), v \rangle, \quad (4.1)$$

for every $v \in \mathbb{R}^n$. The condition (4.1) is imposed by Feinstein and Luenberger [21] to obtain the sufficiency result. This is, of course, satisfied if $H(t, x, p(t))$ is concave in x for every $t \in [0, \infty)$. Thus, the condition (i) of the theorem can be viewed as a strengthening of the necessary conditions (i) and (ii) of Theorem 3.1 under the convexity hypothesis.

If $P(t)$ is negative semidefinite for every $t \in [0, \infty)$ and $\lim_{t \rightarrow \infty} p(t) = 0$, then the condition (ii) of the theorem is satisfied. On the other hand, if $P = 0$, then the condition (ii) of the theorem is equivalent to the transversality condition at infinity:

$$\lim_{t \rightarrow \infty} p(t) = 0. \quad (4.2)$$

For the finite horizon case, sufficient conditions for optimality were given by Mangasarian [26] under the hypothesis that the Hamiltonian H_P is concave and differentiable in (x, u) , whose result was extended by Seierstadt and Sydsæter [33] to the infinite horizon case. Thus, the above observation leads to an extension of the Mangasarian sufficiency theorem with an infinite horizon as follows.

Corollary 4.1. *Suppose that Hypothesis 4.1 is satisfied. Let $(x_0(\cdot), u_0(\cdot))$ be an admissible process for (P) and $p : [0, \infty) \rightarrow \mathbb{R}^n$ be a locally absolutely continuous function with the following properties.*

- (i) $H(t, \cdot, p(t))$ is concave on \mathbb{R}^n for every $t \in [0, \infty)$.
- (ii) $-\dot{p}(t) \in \partial_x H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$.
- (iii) $H_P(t, x_0(t), u_0(t), p(t)) = H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$.
- (iv) $\lim_{t \rightarrow \infty} p(t) = 0$.

Then, $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P).

For the derivation of the transversality condition (4.2) as a necessary condition for optimality, see Aseev and Kryazimskiy [3] and Michel [27] for the smooth case and Ye [39] for the nonsmooth case.

Consider the following transversality condition at infinity:

$$\liminf_{t \rightarrow \infty} \langle p(t), x(t) - x_0(t) \rangle \geq 0, \quad (4.3)$$

for every admissible arc for (P). To obtain the sufficiency result, Seierstadt and Sydsæter [33] imposed the condition (4.3) in addition to the conditions (i) and (ii) of the corollary as well as the differentiability assumption on (L, f) and Feinstein and Luenberger [21] assumed (4.3) for the nonsmooth nonconcave Hamiltonians along with the condition (4.1).

Note that the condition (4.3) is implied by the condition (4.2) if every admissible arc is bounded. However, (4.3) is difficult to check in practice when admissible arcs are unbounded because it involves possible information on the limit behavior of all admissible arcs. The condition (4.2) on its own right needs no such information and improves upon (4.3). Its derivation as a sufficient condition can be found in Cartigny and Michel [14] for the case of smooth concave Hamiltonians with the strong integrability condition on every admissible arc, which is unnecessary in Corollary 4.1.

Let V be an extension of the value function on Ω (which we do not relabel) to $[0, \infty) \times \mathbb{R}^n$ given by $V(t, x) = +\infty$ for $(t, x) \notin \Omega$. We now provide a new sufficient condition in terms of the adjoint inequality for the value function.

Theorem 4.2. *Suppose that Hypothesis 4.1 is satisfied. Let $(x_0(\cdot), u_0(\cdot))$ be an admissible process for (P) such that there exist a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ and a locally absolutely continuous $n \times n$ -symmetric matrix-valued function P on $[0, \infty)$ with the following properties.*

(i) *For a.e. $t \in [0, \infty)$ and for every $v \in \mathbb{R}^n$ and $u \in U(t)$:*

$$\begin{aligned} & H_P(t, x_0(t) + v, u, p(t) - P(t)v) \\ & \leq H_P(t, x_0(t), u_0(t), p(t)) - \langle \dot{p}(t) + P(t)\dot{x}_0(t), v \rangle + \frac{1}{2} \langle v, \dot{P}(t)v \rangle. \end{aligned}$$

(ii) *For every $v \in \mathbb{R}^n$ and $t \in [0, \infty)$:*

$$V(t, x_0(t)) - \langle p(t) + P(t)x_0(t), v \rangle + \frac{1}{2} \langle v, P(t)v \rangle \leq V(t, x_0(t) + v).$$

(iii) $\lim_{t \rightarrow \infty} V(t, x_0(t)) = 0$.

Then, $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P).

For the case in which $P = 0$ in the theorem, the condition (ii) of the theorem reduces to the subgradient inequality for $V(t, \cdot)$:

$$V(t, x_0(t) + v) - V(t, x_0(t)) \geq -\langle p(t), v \rangle,$$

for every $v \in \mathbb{R}^n$. This is, indeed, satisfied if $V(t, x)$ is convex in x for every $t \in [0, \infty)$. Thus, the condition (ii) of the theorem can be viewed as a strengthening of the adjoint inclusions (iii) and (iv) of Theorem 3.1.

While the role of the limit behavior of the value function at infinity in the condition (iii) of the theorem is novel in optimal control theory, it is clarified in the derivation of the sufficiency result for convex problems of calculus of variations with an infinite horizon by Benveniste and Scheinkman [12] and Takekuma [36].

4.2 Proof of Sufficiency Theorems

Let $F : [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R} \cup \{+\infty\}$ be an $\mathcal{L} \times \mathcal{B}^n \times \mathcal{B}^n$ -measurable function. Consider the problem of Lagrange in calculus of variations:

$$\min \mathcal{J}(x(\cdot)) := \int_0^\infty F(t, x(t), \dot{x}(t)) dt, \quad (\text{L})$$

where the minimum is taken over all locally absolutely continuous functions (arcs) $x : [0, \infty) \rightarrow \mathbb{R}^n$ satisfying the initial condition $x(0) = x_0$. We say that $x(\cdot)$ is an *admissible arc* if $\mathcal{J}(x(\cdot))$ is finite and the initial condition is satisfied and that $x_0(\cdot)$ is *locally minimizing* in $T(x_0(\cdot); \varepsilon)$ for the problem (L) if there exists some $\varepsilon > 0$ such that $x_0(\cdot)$ minimizes $\mathcal{J}(x(\cdot))$ over all admissible arcs $x(\cdot)$ satisfying $x(t) \in x_0(t) + \varepsilon B$ for every $t \in [0, \infty)$. The Hamiltonian for (L) is given by:

$$\mathcal{H}(t, x, p) = \sup_{v \in \mathbb{R}^n} \{ \langle p, v \rangle - F(t, x, v) \}.$$

The sufficiency theorem for problems of Bolza due to Zeidan [40] is adapted to the infinite horizon setting here.

Theorem 4.3. *Let $x_0(\cdot)$ be an admissible arc for (L). Suppose that there exist a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$, a locally absolutely continuous $n \times n$ -symmetric matrix-valued function P on $[0, \infty)$ and some $\varepsilon > 0$ with the following properties.*

(i) *For every $v \in \mathbb{R}^n$ and a.e. $t \in [0, \infty)$:*

$$F(t, x_0(t), \dot{x}_0(t) + v) - F(t, x_0(t), \dot{x}_0(t)) \geq \langle p(t), v \rangle.$$

(ii) *For every $v \in \varepsilon B$ and a.e. $t \in [0, \infty)$:*

$$\begin{aligned} & \mathcal{H}(t, x_0(t) + v, p(t) - P(t)v) - \mathcal{H}(t, x_0(t), p(t)) \\ & \leq -\langle \dot{p}(t) + P(t)\dot{x}_0(t), v \rangle + \frac{1}{2}\langle v, \dot{P}(t)v \rangle. \end{aligned}$$

(iii) *For every $\eta > 0$, there exists some $t_0 \in [0, \infty)$ such that:*

$$\frac{1}{2}\langle v, P(t)v \rangle < \langle p(t), v \rangle + \eta \quad \text{for every } v \in \varepsilon B \text{ and } t \in [t_0, \infty).$$

Then, $x_0(\cdot)$ is a locally minimizing arc in $T(x_0(\cdot); \varepsilon)$ for (L).

Define the function $F : [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R} \cup \{+\infty\}$ by:

$$F(t, x, v) = \inf\{L(t, x, u) \mid u \in U(t) : f(t, x, u) = v\}. \quad (4.4)$$

(Note that the infimum over the empty set is taken to be $+\infty$.) An established technique for transforming the problem of optimal control (P) into that of calculus of variations (L) is available here (see Rockafeller [31, 32]). It is based on the observation that the Hamiltonian H for (P) coincides with the Hamiltonian \mathcal{H} for (L) on Ω . Indeed:

$$\begin{aligned} & \sup_{v \in \mathbb{R}^n} \{\langle p, v \rangle - F(t, x, v)\} \\ &= \sup_{v \in \mathbb{R}^n} \{\langle p, v \rangle - \inf\{L(t, x, u) \mid u \in U(t) : f(t, x, u) = v\}\} \\ &= \sup_{u \in U(t)} \{\langle p, f(t, x, u) \rangle - L(t, x, u)\}, \end{aligned}$$

and, hence, for every $(t, x, p) \in [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^n$:

$$\mathcal{H}(t, x, p) = H(t, x, p). \quad (4.5)$$

The following result is a special case of the equivalence theorem due to Rockafeller [32]. (See also Clarke [16, Theorem 5.4.1].)

Equivalence Theorem. *Suppose that Hypothesis 4.1 is satisfied. Let F be given in (4.4). Then, $x_0(\cdot)$ is a minimizing arc for (L) if and only if there is a control function $u_0 : [0, \infty) \rightarrow \mathbb{R}^m$ corresponding to $x_0(\cdot)$ such that $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P).*

Proof of Theorem 4.1. The argument is based on Zeidan [41] and Clarke [16, Theorem 5.4.2]. Hypothesis 4.1 assures that F is $\mathcal{L} \times \mathcal{B}^n \times \mathcal{B}^n$ -measurable and $F(t, \cdot, \cdot)$ is lower semicontinuous for every $t \in [0, \infty)$. (See Clarke [16, Theorem

5.4.1] and Rockafeller [32].) The condition (i) of the theorem and (4.5) imply that:

$$F(t, x_0(t), \dot{x}_0(t)) = L(t, x_0(t), u_0(t)) \quad \text{a.e. } t \in [0, \infty). \quad (4.6)$$

On the other hand, (4.4) implies that $\mathcal{J}(x(\cdot)) \leq J(x(\cdot), u(\cdot))$ for every admissible process $(x(\cdot), u(\cdot))$ for (P) with $x(t) \in x_0(t) + \varepsilon B$ for every $t \in [0, \infty)$. Therefore, to show that $(x_0(\cdot), u_0(\cdot))$ is a locally minimizing process in $T(x_0(\cdot); \varepsilon)$ for (P), it suffices to demonstrate that $x_0(\cdot)$ is a locally minimizing arc in $T(x_0(\cdot); \varepsilon)$ for (L), which is guaranteed if the conditions (i) and (ii) of Theorem 4.3 are shown to be met. It is easy to verify that the condition (i) of Theorem 4.1 and (4.5) imply that:

$$\mathcal{H}(t, x_0(t), p(t)) = \langle p(t), \dot{x}_0(t) \rangle - F(t, x_0(t), \dot{x}_0(t)) \quad \text{a.e. } t \in [0, \infty).$$

Thus, the condition (i) of Theorem 4.3 is satisfied. The condition (i) of Theorem 4.1 and (4.5) again yield the condition (ii) of Theorem 4.3. \square

Proof of Theorem 4.2. Let $(x_0(\cdot), u_0(\cdot))$ be an admissible process for (P) satisfying the conditions of the theorem. It suffices to show that:

$$V(0, x_0(0)) = \int_0^t L(s, x_0(s), u_0(s)) ds + V(t, x_0(t)), \quad (4.7)$$

for every $t \in [0, \infty)$, because taking the limit as $t \rightarrow \infty$ in (4.7) yields:

$$V(0, x_0(0)) = \int_0^\infty L(s, x_0(s), u_0(s)) ds,$$

from which the optimality of $(x_0(\cdot), u_0(\cdot))$ follows.

Suppose to the contrary that (4.7) is not true. By the definition of V , there exists some $\eta > 0$ such that:

$$V(0, x_0(0)) + \eta < \int_0^T L(t, x_0(t), u_0(t)) dt + V(T, x_0(T)), \quad (4.8)$$

for some $T \in [0, \infty)$. Again by the definition of V , there exists an admissible process $(x(\cdot), u(\cdot))$ for (P) such that:

$$\int_0^\infty L(t, x(t), u(t)) dt < V(0, x_0(0)) + \eta.$$

Thus, the inequality (4.8) implies the existence of an admissible process $(x(\cdot), u(\cdot))$ for (P) such that:

$$\int_0^T L(t, x(t), u(t)) dt + V(T, x(T)) < \int_0^T L(t, x_0(t), u_0(t)) dt + V(T, x_0(T)). \quad (4.9)$$

It follows from (4.4) that:

$$L(t, x(t), u(t)) - L(t, x_0(t), u_0(t)) \geq F(t, x(t), \dot{x}(t)) - F(t, x_0(t), \dot{x}_0(t)), \quad (4.10)$$

a.e. $t \in [0, \infty)$. As noted in the proof of Theorem 4.1, the conditions (i) and (ii) of Theorem 4.3 are satisfied for $\varepsilon = +\infty$. Thus, integrating the inequality (4.10) together with the condition (ii) of the theorem yield:

$$\int_0^T [L(t, x(t), u(t)) - L(t, x_0(t), u_0(t))] dt \geq -(V(T, x(T)) - V(T, x_0(T))),$$

which contradicts (4.9). \square

5 Necessary and Sufficient Conditions for Optimality

In this section, we derive the necessary and sufficient conditions for optimality under convexity hypotheses. Convex problems of optimal control examined here clarify the role of the limit behavior of the value function for a complete characterization of optimality. Furthermore, we investigate the role of transversality conditions at infinity and derive them as necessary and sufficient conditions for optimality under some additional assumptions.

5.1 Limit Behavior of the Value Function at Infinity

As demonstrated in the Appendix, the hypothesis that follows is derived from the convexity hypothesis on the primitive (L, f, Ω, U) .

Hypothesis 5.1. (i) $\Omega(t) \times U(t)$ is convex for every $t \in [0, \infty)$.

(ii) $H(t, \cdot, p)$ is concave on \mathbb{R}^n for every $(t, p) \in [0, \infty) \times \mathbb{R}^n$.

(iii) $V(t, \cdot)$ is convex on $\Omega(t)$ for every $t \in [0, \infty)$.

Theorem 5.1. *Suppose that Hypotheses 3.1, 4.1 and 5.1 are satisfied. An admissible process $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P) if and only if the following conditions are satisfied.*

(i) *There exists a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ such that*

(a) $-\dot{p}(t) \in \partial_x H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$,

(b) $H_P(t, x_0(t), u_0(t), p(t)) = H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$,

(c) $-p(t) \in \partial_x V(t, x_0(t))$ for every $t \in [0, \infty)$,

(ii) $\lim_{t \rightarrow \infty} V(t, x_0(t)) = 0$.

5.2 Transversality Condition at Infinity

To derive a sharper result on the transversality condition at infinity, one must specify the problem in more detail. The following hypothesis is in accordance with the standard conditions in economic growth theory such as Benveniste and Scheinkman [12] and Takekuma [36].

Hypothesis 5.2. (i) $\Omega(t) \subset \mathbb{R}_+^n$ for every $t \in [0, \infty)$.

(ii) $0 \in U(t)$ a.e. $t \in [0, \infty)$.

(iii) $f(t, 0, 0) = 0$ a.e. $t \in [0, \infty)$.

(iv) $L(t, 0, 0) \leq 0$ a.e. $t \in [0, \infty)$.

(v) $L(t, \cdot, u)$ is nondecreasing on $\Omega(t)$ for every $u \in U(t)$ a.e. $t \in [0, \infty)$.

Theorem 5.2. *Suppose that Hypotheses 3.1, 4.1, 5.1 and 5.2 are satisfied. An admissible process $(x_0(\cdot), u_0(\cdot))$ is a minimizing process for (P) if and only if there exists a locally absolutely continuous function $p : [0, \infty) \rightarrow \mathbb{R}^n$ such that*

- (i) $-\dot{p}(t) \in \partial_x H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$;
- (ii) $H_P(t, x_0(t), u_0(t), p(t)) = H(t, x_0(t), p(t))$ a.e. $t \in [0, \infty)$;
- (iii) $-p(t) \in \partial_x V(t, x_0(t))$ for every $t \in [0, \infty)$;
- (iv) $\lim_{t \rightarrow \infty} \langle p(t), x_0(t) \rangle = 0$.

While the transversality condition at infinity:

$$\lim_{t \rightarrow \infty} \langle p(t), x_0(t) \rangle = 0,$$

is familiar in economic growth theory, the derivation of this condition as a necessary and sufficient condition for optimality in optimal control is novel in the literature. Aseev and Kryazimskiy [3] obtained this as a necessary condition for optimality under somewhat restrictive smoothness assumptions with quasi-linear control systems.

For convex problems of Lagrange in calculus of variations, Araujo and Scheinkman [2], Benveniste and Scheinkman [12] and Takekuma [36] obtained this condition as a necessary and sufficient condition for optimality for the nonsmooth case and Becker and Boyd [10] did so for the smooth case. For the derivation of the variant of this condition as a necessary condition in nonconvex smooth problems of Lagrange in calculus of variations with unbounded integrands, see Kamihigashi [25].

A Properties of the Value Function and the Hamiltonian

We have assumed in Hypothesis 3.1(v) that $V(t, \cdot)$ is Lipschitz of rank K on $x_0(t) + \varepsilon B$ for every $t \in [0, \infty)$. In Appendix A.1, we demonstrate the continuity of V on the ε -tube about $x_0(\cdot)$ and the Lipschitz continuity of $V(t, \cdot)$ under the existence of a minimizing process for any initial condition. For the finite horizon case, the result is well-known (see, for instance, Vinter [38, Proposition 12.3.5]), but some intricate arguments are involved for the infinite horizon case concerning the integrability of the integrand and the interiority of the minimizing arcs.

The convexity of the value function is proven in Appendix A.2 under some additional assumptions. The concavity of the Hamiltonian is demonstrated in Appendix A.3.

A.1 Lipschitz Continuity of the Value Function

Theorem A.1. *Suppose that Hypothesis 3.1 is satisfied. Then, V is continuous on the ε -tube about $x_0(\cdot)$.*

We extend the notion of an ε -tube. Let $\theta_\varepsilon : [0, \infty) \rightarrow \mathbb{R}$ be a positive measurable function given by $\theta_\varepsilon(s) = \varepsilon \exp(\int_0^s k_f(\tau) d\tau)$ for $s \in [0, \infty)$ with $\varepsilon > 0$. An *extended ε -tube* about continuous function $x : [t, \infty) \rightarrow \mathbb{R}^n$ is of the form:

$$T(x(\cdot); \theta_\varepsilon) := \{(s, x) \in [t, \infty) \times \mathbb{R}^n \mid x \in x(s) + \theta_\varepsilon(s)B\}.$$

Hypothesis A.1. There exists some $\varepsilon > 0$ such that, for every $(t, x) \in \Omega$, there exists a minimizing process $(x(\cdot | t, x), u(\cdot | t, x))$ on $[t, \infty)$ with the initial condition $x(t | t, x) = x$ such that the extended ε -tube about $x(\cdot | t, x)$ is contained in Ω .

Without loss of generality, we may assume that $x_0(\cdot) = x(\cdot | 0, x_0)$.

Theorem A.2. Suppose that the conditions (i) to (iv) of Hypothesis 3.1, and Hypothesis A.1, are satisfied. Then, $V(t, \cdot)$ is Lipschitz of rank K on $x_0(t) + \frac{\varepsilon}{2}B$ for every $t \in [0, \infty)$.

A.2 Convexity of the Value Function

Define the set-valued mapping $\Gamma : \Omega \rightrightarrows \mathbb{R} \times \mathbb{R}^n$ by:

$$\Gamma(t, x) = \{(v, w) \in \mathbb{R} \times \mathbb{R}^n \mid \exists u \in U(t) : w \geq L(t, x, u), v = f(t, x, u)\},$$

and the set M by:

$$M = \{(t, x, u) \in [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^m \mid (x, u) \in \Omega(t) \times U(t)\}.$$

Hypothesis A.2. (i) L and f are continuous on M .

(ii) $-\infty < V(t, x)$ for every $(t, x) \in \Omega$.

(iii) Ω and $\text{graph}(U)$ are closed.

(iv) $\Omega(t)$ is convex for every $t \in [0, \infty)$.

(v) $\Gamma(t, \cdot) : \Omega(t) \rightrightarrows \mathbb{R} \times \mathbb{R}^n$ has the convex graph for every $t \in [0, \infty)$.

The condition (ii) of the hypothesis is automatically satisfied if Hypothesis A.1 is imposed. The conditions (iv) and (v) of the hypothesis are somewhat stronger than the standard convexity hypothesis guaranteeing the existence of a minimizing process that $\Gamma(t, \cdot)$ is convex-valued for every $t \in [0, \infty)$. (See Balder [6], Bates [8], Baum [9], Bell et al. [11], Feinstein and Luenberger [21].)

Theorem A.3. Suppose that Hypothesis A.2 is satisfied. Then, $V(t, \cdot)$ is convex on $\Omega(t)$ for every $t \in [0, \infty)$.

A.3 Concavity of the Hamiltonian

The concavity of the Hamiltonian is subtler than the convexity of the value function. Specifically, Hypothesis A.2, guaranteeing the convexity of the value function $V(t, x)$ in x , is insufficient to establish the concavity of the Hamiltonian $H(t, x, p)$ in x .

Note that, by (4.5), for every $(t, x, p) \in [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^n$:

$$H(t, x, p) = \sup_{v \in \mathbb{R}^n} \{\langle p, v \rangle - F(t, x, v)\}.$$

Thus, $H(t, x, p)$ is concave in x if $F(t, x, v)$ is convex in (x, v) . As shown by Feinstein and Luenberger [21], the following hypothesis is sufficient for $F(t, \cdot, \cdot)$ to be a convex function on $\Omega(t) \times \mathbb{R}^n$ for every $t \in [0, \infty)$, from which the concavity of the Hamiltonian follows.

- Hypothesis A.3.** (i) $\Omega(t) \times U(t)$ is convex for every $t \in [0, \infty)$.
- (ii) $L(t, \cdot, \cdot)$ is convex on $\Omega(t) \times U(t)$ for every $t \in [0, \infty)$ and $L(t, x, \cdot)$ is nondecreasing on $U(t)$ for every $(t, x) \in \Omega$.
- (iii) $f(t, \cdot, \cdot) : \Omega(t) \times U(t) \rightarrow \mathbb{R}^n$ is concave for every $t \in [0, \infty)$.
- (iv) $f(t, \cdot, U(t)) : \Omega(t) \rightrightarrows \mathbb{R}^n$ has the convex graph for every $t \in [0, \infty)$.
- (v) For every $v \in f(t, x, U(t))$ and $u \in U(t)$ with $v \leq f(t, x, u)$ and $x \in \Omega(t)$, there exists some $u' \in U(t)$ such that $u' \leq u$ and $v = f(t, x, u')$.

Theorem A.4. $H(t, \cdot, p)$ is concave on \mathbb{R}^n for every $(t, p) \in [0, \infty) \times \mathbb{R}^n$ if Hypothesis A.3 is satisfied.

Note also that the conditions (i) to (iii) and (v) of the hypothesis imply Hypothesis A.2 and, thus, the convexity of the value function.

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